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COOLING EFFECTIVENESS OF A HYBRID MICROCLIMATE GARMENT

BY

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A prototype microclimate cooling garment that would allow the wearer to connect to either an air or a liquid cooling unit was tested and compared with existing air and liquid vests. Five male soldiers wore the three garments (hybrid, air, and liquid) on different days while walking on a treadmill ~~at 1.0 m sec⁻¹ (2.2 mi hr⁻¹), 0% grade)~~ in a climatically controlled environment. The chamber conditions were: dry bulb temperature, 38°C (100°F); relative humidity, 20%. The exercise generated a 332-W ~~(1133 Btu hr⁻¹)~~ metabolic rate. The average metabolic rate (including rest periods) was 287 W. ~~(980 Btu hr⁻¹)~~ The hybrid garment, in either mode, performed as well as the individual air and liquid garments. Though the hybrid vest succeeded physiologically, comfort and fit problems were revealed that will require major changes in the next iteration.

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PREFACE

This study was conducted to evaluate the performance of a prototype cooling garment that operated with either air or liquid as the cooling medium. The data gathered — cooling levels, physiological responses and human factors observations — have been analyzed and presented herein to provide guidance in the design of the next generation garment.

The research was conducted jointly by the U.S. Army Research Institute of Environmental Medicine (USARIEM) and the U.S. Army Natick RD&E Center (NRDEC), Program Element No. 63747.

The authors wish to acknowledge the high level of effort and cooperation displayed by the test subjects throughout the study.

Our thanks is also extended to Mr. Il Young Kim for his artistic contribution.

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INTRODUCTION

Microclimate cooling has been introduced to the field as standard equipment on the M1A1 Abrams tank. Other combat vehicle Program Managers are studying the use of microclimate systems, and the trend appears to favor the selection of air as the cooling medium. Certain scenarios require a mounted soldier to leave the vehicle for an extended period of time. It is desired to provide cooling to the soldier during this period. Existing technology indicates that the use of liquid cooling for dismounted operations is more viable than air cooling because, in general, the components are smaller, lighter, and require less power to deliver a comparable cooling rate. All of these factors affect portability of the proposed system. In an effort to ease the logistical burdens of fielding two different cooling garments, an attempt has been made to combine an air distribution system and a liquid circulation loop into one garment. The result is the hybrid microclimate cooling garment.

A study was conducted to determine the effectiveness of the new garment while operating as either an air distribution garment or a liquid circulation garment, with comparison to the existing air and liquid cooling vests. Data gathered will form the framework for generating the next design iteration.

The investigation was conducted by the U.S. Army Research Institute of Environmental Medicine (USARIEM) and Natick.

TEST DESCRIPTION

Subjects.

Five male soldiers served as test subjects. All volunteered and were allowed to terminate their participation at any time if they desired. Physical characteristics of the subjects were (mean +/- standard deviation): age, 24.4 +/- 5.3 years; height, 174.6 +/- 3.8 cm; mass, 65.9 +/- 12.1 kg; body surface area, 1.79 +/- 0.16 m^2. Testing was conducted in midsummer. The subjects were heat acclimated for five days prior to beginning the study.

Climatic Conditions.

The environment for each session was maintained at 38°C (100°F) dry bulb temperature and 11.5°C (53°F) dew point (20% relative humidity). The wind speed was 1.12 $m \cdot s^{-1}$ (2.5 $mi \cdot hr^{-1}$).

Metabolic Heat Load.

Each test consisted of three rest/work cycles (40 minutes and ten minutes, respectively). The subjects walked on a treadmill at 1.0 $m \cdot s^{-1}$ (2.2 $mi \cdot hr^{-1}$), 0% grade during their work periods. The average, measured metabolic rate during exercise was 332 W (1133 $Btu \cdot hr^{-1}$). The overall metabolic rate (including rest) was 287 W (980 $Btu \cdot hr^{-1}$).

Clothing and Equipment.

The test subjects wore (in order, from the skin outward) a T-shirt, cooling vest, combat vehicle crewman (CVC) fragmentation protective vest, CVC Nomex coveralls, chemical/biological (CB) overgarment (pants and jacket), M-17 gas mask, butyl rubber hood, CB butyl rubber gloves with

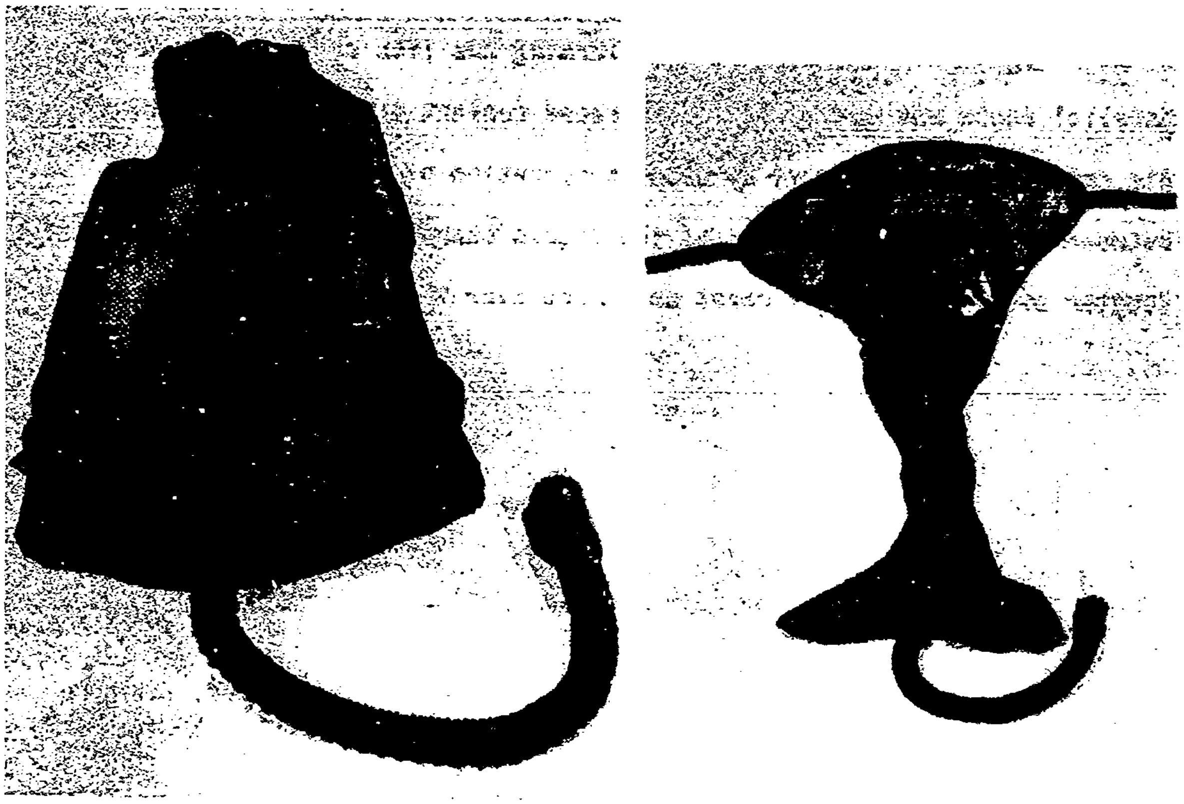
cotton liners, and CB butyl rubber overboots. The filter elements were removed from the masks to facilitate breathing.

Cooling Garments.

The hybrid microclimate cooling garment (Fig. 1) consisted of two parallel circuits, one for air and the other for liquid. Two layers of polyurethane-coated nylon, heat-sealed into panels, formed a continuous channel through which a chilled liquid was circulated. The coolant flowed in series from the front-right torso region, to the back, to the front-left torso, and then doubled back along the opposite route. The concept behind this layout was to eliminate a "cold" region at the vest inlet and a "hot" region at the vest outlet. Turning the flow channel back along a parallel route was to provide an averaged coolant temperature to the skin. Air cooling was introduced by the incorporation of perforated tubes between the straight portions of the liquid channel. Two tubes were located over the wearer's chest and three over the back.

Figure 1. Hybrid microclimate cooling garment.

The air garment used was the Vest, Microclimate Cooling: Air, NSN 8415-01-217-5634 (Fig. 2). The vest consisted of a manifold assembly which split the air entering the vest and distributed it over the chest, neck, and back. The manifolds and hoses were kept in place by attachment to an open-weave, Nomex carrier. Effectiveness of the vest had been documented in earlier studies (1,2). Air was supplied to both the air vest and hybrid-air vest at 4.8 +/- 0.4 $L \cdot s^{-1}$ (10.1 +/- 0.8 $ft^3 \cdot min^{-1}$). The air was at a dry bulb temperature of 28.3 +/- 1.4 °C (82.9 +/- 2.5 °F) and had a dew point of 15.6 °C (60.1 °F) (45% relative humidity).



(a) (b)

Figure 2. Air microclimate cooling vest.

(a) folded view; (b) unfolded view.

The liquid cooling garment (Fig. 3) was constructed of polyurethane-coated nylon, but used a diffused, less well-defined flow pattern than the hybrid garment (Fig. 4). Chilled liquid entered at the back of the collar and flowed in parallel to each side of the chest, over the shoulders to the lower back and then up the back to an exit port located just below the collar.

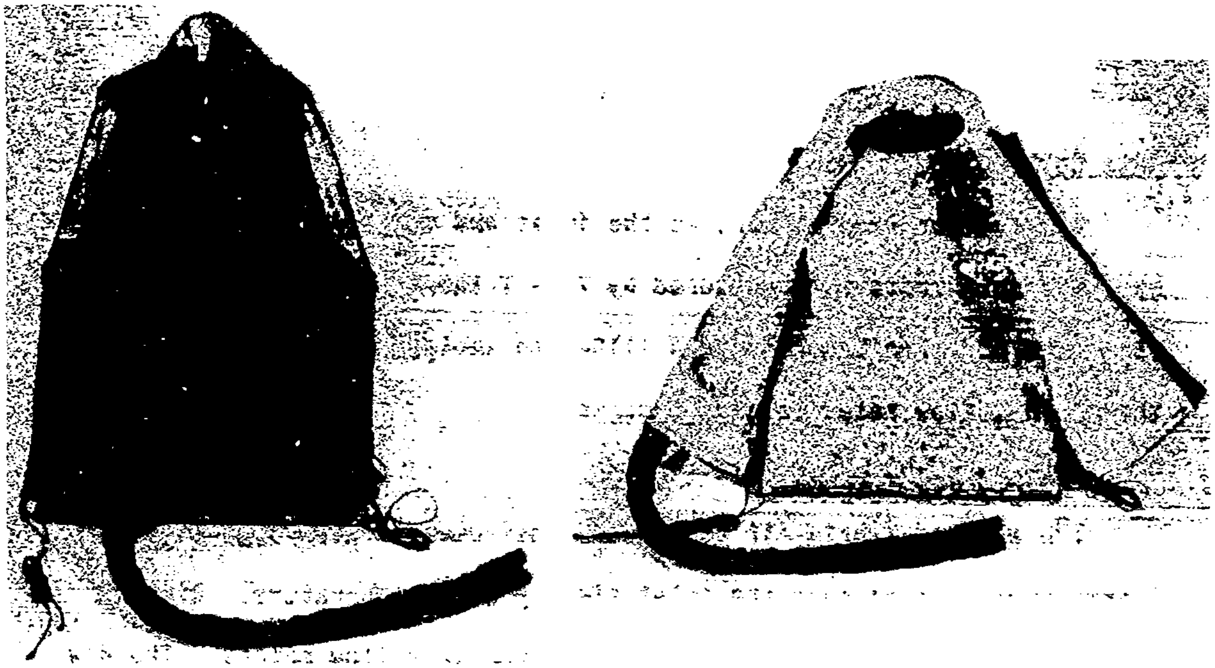


Figure 3. Liquid microclimate cooling garment.

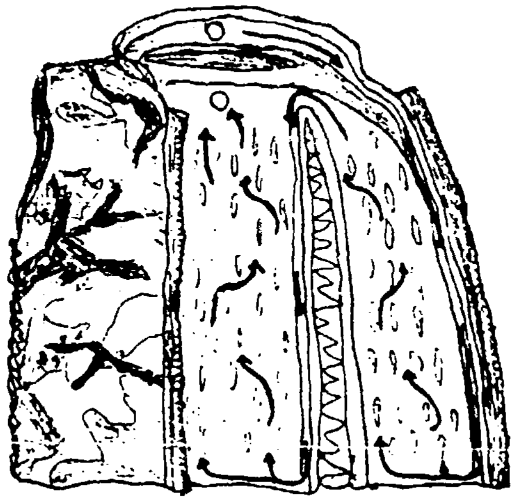


Figure 4. Liquid cooling garment flow pattern.

Cooling studies using this vest had also been conducted prior to its selection for the test (3). A 10% percent propylene glycol and water solution was circulated at a rate of 6.3×10^{-3} $L \cdot s^{-1}$ ($50\ lb \cdot hr^{-1}$). The temperature of the coolant entering the vests was 25.0 +/- 0.8 ^{o}C (77.0 +/- 1.4 ^{o}F). The coolant flow rate and inlet temperature were the same for both the liquid and hybrid-liquid garments.

Data Collection.

The coolant temperatures at the inlet and outlet of the liquid and hybrid-liquid vests were measured by Type T thermocouples placed in the flow streams. Two Brooks Type 6-1110-6 rotameters were used to monitor the coolant flow rates to the garments.

The air and hybrid-air vests were instrumented with Type T thermocouples to measure the inlet air dry bulb temperature. Airflow rates were determined using Datametrics Type 1202 flow meters. The dew point temperature of the air was set by controlling the temperature of the saturated air leaving the air supply/conditioning unit.

All thermocouples and air flow meters were connected to a Hewlett-Packard Model 3497A scanner. The voltages were fed to a Hewlett-Packard Model 9836 CPU for conversion to temperature and flow rate values and storage onto a floppy disk. Output from the CPU was to a plotter and printer (Hewlett-Packard Models 7470A and 2631A, respectively) to provide real-time monitoring of the systems.

The rate of heat absorbed ($\dot{Q}$) by either of the liquid cooled garments was calculated by multiplying the coolant flow rate ($\dot{m}$) by the heat capacity of the coolant (Cp) and the temperature difference between the inlet and outlet of the vest (ΔT) (Eq. 1).

$$\dot{Q} = \dot{m} \times Cp \times \Delta T \qquad (1)$$

$$Cp = 0.96\ cal \cdot g^{-1} \cdot {}^{o}C^{-1}\ (0.96\ Btu \cdot lb^{-1} \cdot {}^{o}F^{-1})$$

A method of assessing the dry bulb temperature and saturation level of the exit air which was both reliable and unobtrusive could not be arranged. Therefore, no direct measurement of the cooling rate achieved by the air garments was obtained. After calculation of the liquid cooling rates, the data was subjected to an analysis of variance (ANOVA) and Duncan's multiple range test to determine any significant differences between the systems.

Physiological measurements were made by USARIEM. The test was terminated after 150 minutes or if a subject's core temperature reached 39.5^{o}C (103.1^{o}F) or if his heart rate exceeded 180 beats per minute for more than five minutes during or immediately following exercise.

RESULTS

Cooling Performance.

There was no significant difference between the levels of heat removed by the liquid and hybrid-liquid garments. The measured values were 92.7 +/- 10.2 W (316.5 +/- 34.8 $Btu \cdot hr^{-1}$) and 84.9 +/- 12.3 W (289.8 +/- 42.0 $Btu \cdot hr^{-1}$), respectively.

As explained in the previous section, no direct measurement of the heat removed by the air garments was possible.

Physiology.

Comparing the liquid and hybrid-liquid garments, no significant differences were found between final core temperatures, T_{re}, 37.7 $^{\circ}$C (99.9 $^{\circ}$F); change in core temperature, T_{re}, 0.77 C$^{\circ}$ (1.4 F$^{\circ}$); final heart rate, HR, 140 $b \cdot min^{-1}$; or whole body sweat rate, SR, 14.3 $g \cdot min^{-1}$ (the reported means are for the combined data sets).

Likewise, no significant differences were found for these parameters when the air and hybrid-air garments were compared: T_{re}, 37.6 $^{\circ}$C (99.7°F); T_{re}, 0.48 C$^{\circ}$ (0.86 F$^{\circ}$); HR, 130 $b \cdot min^{-1}$; and SR, 12.6 $g \cdot min^{-1}$ (again, the reported means are for the combined data sets). Further analysis of the measured physiological parameters may be found in ref. 4.

Subjective evaluations by the subjects yielded a mean value of 12.2 (light) for their perceived level of exertion during the exercise sessions (7 = very, very easy; 19 = very, very hard) and a thermal sensation of 5.2 (warm; 0.0 = unbearably cold; 8.0 = unbearably hot). All subjects in all tests were able to complete the 150 minute work/rest regime.

Human Factors.

The following shortcomings in the hybrid vest were noted during the study:

(1) the liquid umbilical was too short -- it was barely able to protrude through the outer layers of clothing,

(2) the air umbilical got in the way when not being used,

(3) the garment did not fit well at the lower back due to its stiffness -- proper contact in the liquid mode is important,

(4) the garment was too long -- it chafed the front of the thighs on the smaller subjects,

(5) the collar was too high in the back of the neck.

DISCUSSION

The study showed the general feasibiltiy of combining the two functions of air distribution and liquid circulation into one garment. In both modes, the physiological data (and in the case of liquid cooling, the heat removal values) indicated the ability of the hybrid garment to function as effectively as the existing air and liquid vests at the work rate and environmental conditions chosen.

The next iteration of the hybrid vest must maintain the level of performance demonstrated in the study while eliminating the comfort and fit problems highlighted in the previous section. The present design of the hybrid garment should allow for the necessary alterations to be made without deleterious impact on performance. Shortening the vest and streamlining the collar can be done with no reduction of liquid-cooling surface area. The liquid umbilical, once lengthened, should run parallel to and be attached to the existing air umbilical hose. The connectors for each should readily permit them to be coupled next to each other. By incorporating these engineering changes with information gathered by a sizing study, a fieldable hybrid garment design can confidently proceed.

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